Massive Stars in Interacting Binaries
ASP Conference Series, Vol. 367, 2007
N. St-Louis & A.F.J. Moffat

Accretion/Decretion Disk Dynamics in Be/X-ray Binaries

A. T. Okazaki

Faculty of Engineering, Hokkai-Gakuen University, Toyohira-ku, Sapporo 062-8605, Japan

Abstract. We study the dynamics of disk systems in Be/X-ray binaries, based on the results from three-dimensional Smoothed Particle Hydrodynamics simulations. We find that the Be decretion disk is tidally/resonantly truncated at a radius smaller than the periastron distance, except in systems with very high orbital eccentricities and/or large inclination angles. In misaligned systems, the Be disk precesses little when the mass is supplied continuously from the Be star, whereas it precesses in the retrograde direction when no mass is supplied. The truncated disk around the Be star in an eccentric orbit makes the mass transfer towards the neutron star reduced and strongly phase-dependent. The accretion disk, which is necessarily time-dependent, is persistent in systems with a moderate orbital eccentricity, whereas it is transient in highly eccentric systems.

1. Introduction

Be/X-ray binaries are the largest subclass of high-mass X-ray binaries. They consist of a Be star and a neutron star. The orbit is wide ($10\,\mathrm{d} \lesssim P_{\rm orb} \lesssim 300\,\mathrm{d}$) and mostly eccentric ($e \gtrsim 0.3$). Most of the Be/X-ray binaries exhibit only transient X-ray activity, the features of which suggest complicated interactions between the Be star and the neutron star.

Apart from being the dominant subclass of high-mass X-ray binaries, Be/X-ray binaries are important as a laboratory for studying the physics of the tidal interaction, the mass transfer, and the accretion process in eccentric binaries. They are also unique in the sense that both Be stars and neutron stars have nearly Keplerian disks. The disk around the Be star is formed by the viscous decretion of material ejected from the Be star (Lee, Saio, & Osaki 1991), whereas that around the neutron star is formed by the viscous accretion of material transferred from the Be disk. Therefore, in Be/X-ray binaries, the mass is transferred from the decretion disk to the accretion disk, which had not been studied until quite recently.

Based on the viscous decretion disk model, Negueruela & Okazaki (2001) and Okazaki & Negueruela (2001) semi-analytically showed that the coplanar Be disk in Be/X-ray binaries is truncated at a radius smaller than the periastron distance, as long as $\alpha_{\rm SS} \ll 1$, where $\alpha_{\rm SS}$ is the Shakura-Sunyaev viscosity parameter. The result agrees with the observations (Reig et al. 1997; Zamanov et al. 2001) and has been confirmed later by numerical simulations for a system with a short orbital period and a moderate orbital eccentricity (Okazaki et al. 2002). Using the data from a simulation by Okazaki et al. (2002), Hayasaki

& Okazaki (2004) performed numerical simulations of the accretion flow and showed that there exists a persistent accretion disk around the neutron star. See Figure 1 for a schematic diagram of the interactions in Be/X-ray binaries.

In this paper, we explore the dynamics of both disks in Be/X-ray binaries, using three dimensional Smoothed Particle Hydrodynamics (SPH) simulations for a wide range of orbital parameters. One of our simulations is for the accretion disk formation, while the others are for the Be disk evolution.

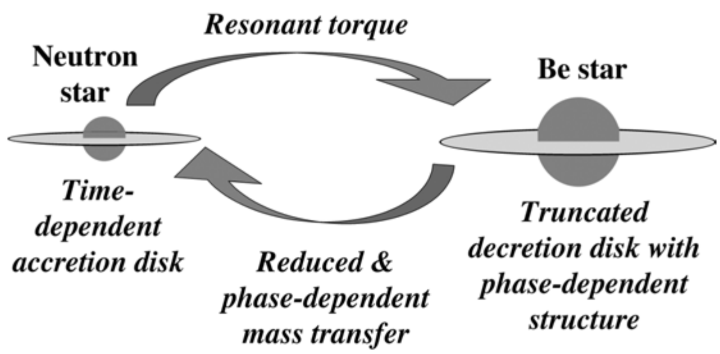

Figure 1. Schematic diagram of the interactions in Be/X-ray binaries.

2. Numerical Model

We use a 3D SPH code, in which the Be disk (and the accretion disk in one simulation) is modeled by an ensemble of gas particles of negligible masses and the Be star and the neutron star by two sink particles with corresponding masses (Okazaki et al. 2002; Hayasaki & Okazaki 2004; see also Bate, Bonnell, & Price 1995). For simplicity, we assume that the disks are isothermal at the temperature of half the effective temperature of the Be star and have the viscosity parameter $\alpha_{\rm SS} = 0.1$. The orbital period is fixed at $P_{\rm orb} = 24.3\,{\rm d}$. We set the binary orbit on the x-z plane with the major axis along the x-axis. At $t = 0$, the neutron star is at apastron. In a simulation of the accretion disk formation, we set the inner simulation boundary at $r = 5 \times 10^{-3}a$, where a is the semi-major axis. In the other simulations, we assume that the neutron star has a variable accretion radius depending on the instantaneous binary separation. The mass ejection mechanism from the Be star is modeled by constant injection of gas particles at a radius just outside the equatorial surface. For the Be star, we take a B0V star of $M_* = 18M_\odot$, $R_* = 8R_\odot$, and $T_{\rm eff} = 26,000\,{\rm K}$, while for the neutron star, we take $M_X = 1.4M_\odot$ and $R_X = 10^6\,{\rm cm}$.

3. Be Disk Dynamics

3.1. Coplanar Systems

Figure 2 shows the surface-density evolution of the viscous decretion disk around the Be star. Panels (a)-(c) are for coplanar systems with different eccentricity, *e*. [Panel (d) is for a misaligned system and will be dicussed in the following subsection.] As shown in Figure 2, the decretion disk around the Be star is tidally/resonantly truncated at a radius smaller than the periastron distance for a wide range of eccentricity. We have found that the tidal/resonant truncation works, except for systems with extremely high eccentricity ($e \gtrsim 0.8$). The truncation is most efficient for a circular binary and becomes less efficient for a higher eccentricity.

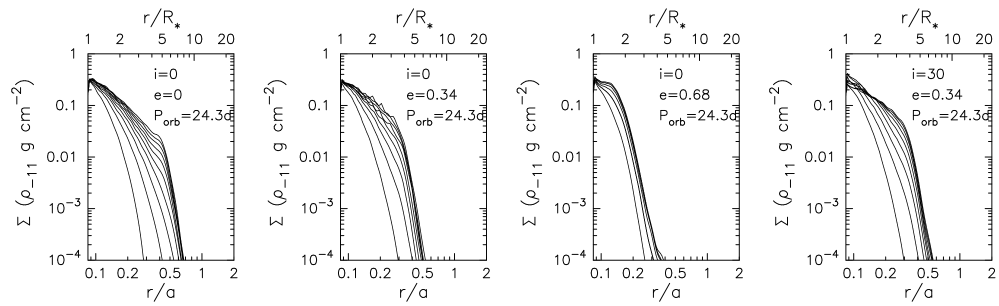

Figure 2. Surface-density evolution of the Be decretion disk for (a) $i = 0°$ and $e = 0$, (b) $i = 0°$ and $e = 0.34$, (c) $i = 0°$ and $e = 0.68$, and (d) $i = 30°$ about the y-axis and $e = 0.34$, where i is the angle between the mid-plane of the Be disk and the orbital plane. The time interval between adjacent contours is $5P_{\rm orb}$. $\rho_{-11} = \rho_0/10^{-11}{\rm g\,cm^{-3}}$, where ρ_0 is the base density of the disk.

3.2. Misaligned Systems

Figure 2(d) shows the surface-density evolution of the Be disk in a misaligned system for $e = 0.34$, where the Be disk is inclined from the orbital plane by 30° about the y-axis. It should be noted that the resonant truncation works for misaligned systems as it does for coplanar ones. For a higher inclination angle i, however, the truncation is less efficient. Little truncation is seen for $i > 60°$.

From our simulations for misaligned systems, we have also found that Be decretion disks show little precession when the material is continuously supplied from the Be star. Interestingly, when the mass supply is turned off and the torque from the star is lost, the Be disk begins to precess in the retrograde direction at a rate in agreement with the analytical precession rate modified to include the effect of the orbital eccentricity (Bate et al. 2000 for inclusion of the effect of orbital eccentricity to the formula by Papaloizou & Terquem 1995)

4. Accretion Disk Dynamics

4.1. Moderately Eccentric Systems

Recently, Hayasaki & Okazaki (2004) studied the accretion flow around the neutron star in a Be/X-ray binary with a short period ($P_{\rm orb} = 24.3\,{\rm d}$) and a moderate eccentricity ($e = 0.34$), using a 3D SPH code and the simulation data by Okazaki et al. (2002) as the outer boundary condition. They found that a

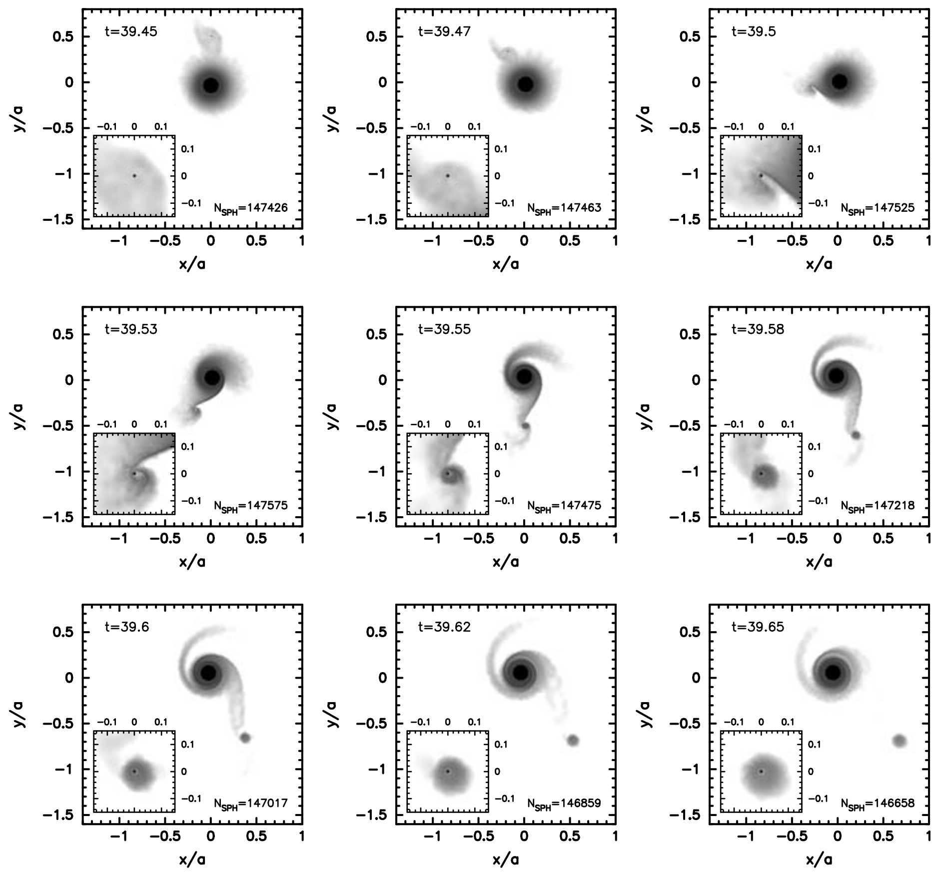

Figure 3. Snapshots of the accretion disk formation in a coplanar system with $e = 0.68$, which cover $0.2P_{\rm orb}$ around the periastron passage. Each panel shows the surface density in a range of 3.5 orders of magnitude in the logarithmic scale. The dark spot near the origin is the Be star. At the third panel ($t = 39.5P_{\rm orb}$), the neutron star is at the periastron. The inset gives a close-up of the accretion disk around the neutron star, of which the accretion radius is $5 \times 10^{-3}a$.

time-dependent accretion disk is formed around the neutron star and that it grows secularly, because the mass-accretion rate onto the neutron star is much smaller than the mass-capture rate by the neutron star in their moderately eccentric system. Therefore, it is likely that Be/X-ray binaries with moderate orbital eccentricities have persistent accretion disks around the neutron star, even if they exhibit no periodic (Type I) X-ray outbursts.

4.2. Highly Eccentric Systems

Figure 3 gives snapshots of the accretion disk formation in a coplanar system with $e = 0.68$. As seen in Figure 3, an accretion disk is formed around the neutron star at periastron, when the material in the outermost part of the Be disk is transferred to the neutron star for a very short period of time. Most of the material transferred from the Be disk accretes onto the neutron star by the

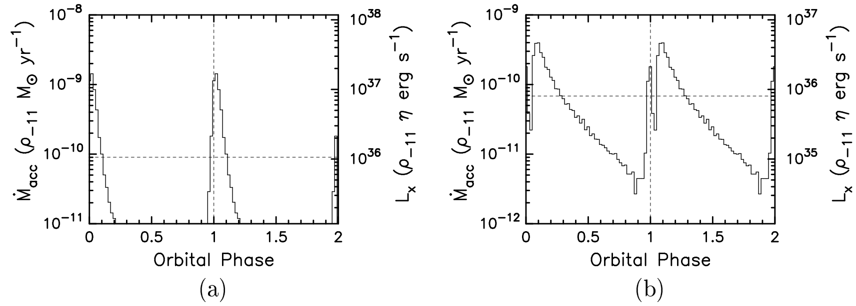

Figure 4. Orbital-phase dependence of (a) the mass capture rate by the neutron star and (b) the accretion rate onto the neutron star. To reduce the fluctuation noise, the data is folded on the orbital period over $10P_{\rm orb}$. The periastron passage of the neutron star, which occurs at phase 0, is denoted by the vertical dashed line. The right axis shows the X-ray luminocity corresponding to the mass-capture/mass-accretion rate.

next periastron passage. Thus, the accretion disk in this highly eccentric system is not persistent and has a life-time shorter than the orbital period, unlike the counterparts in moderately eccentric systems.

Figure 4 shows the orbital-phase dependence of the mass capture rate by the neutron star (left) and the accretion rate onto the neutron star (right). Note that the accretion-rate profile has two peaks, a precursor and the major peak. This is because the specific angular momentum of the transferred mass from the Be disk has a strong phase-dependence.

Finally, it is important to note that the X-ray luminosity ($\sim 5\times 10^{36}{\rm erg\,s^{-1}}$) corresponding to the peak mass-accretion rate of about $4\times 10^{-10} M_\odot\,{\rm yr}^{-1}$ shown in Figure 4(b) enters a typical luminosity range of the Type I X-ray outbursts in Be/X-ray binaries. This strongly suggests that, in the framework of the truncated Be disk model for Be/X-ray binaries, Type I X-ray outbursts are the phenomena most frequently seen in highly eccentric systems.

References

Bate, M.R., Bonnell, I.A., Clarke, C.J., Lubow, S.H., Ogilvie, G.I., Pringle, J.E., Tout, C.A. 2000, MNRAS, 317, 773

Bate, M. R., Bonnell, I. A., & Price, N. M. 1995, MNRAS, 285, 33

Hayasaki, K. & Okazaki, A. T. 2004, MNRAS, 350, 971

Lee, U., Saio, H., & Osaki, Y. 1991, MNRAS, 250, 432

Negueruela, I. & Okazaki, A. T. 2001, A&A, 369, 108

Okazaki, A. T. & Negueruela, I. 2001, A&A, 377, 161

Okazaki, A. T., Bate, M. R., Ogilvie, G. I., & Pringle, J. E. 2002, MNRAS, 337, 967

Papaloizou, J.C.B., & Terquem, C. 1995, MNRAS, 274, 987

Reig, P., Fabregat, J. & Coe, M. J. 1997, A&A, 322, 193

Zamanov, R. K., Reig, P., Mart, J., Coe, M. J., Fabregat, J., Tomov, N.A., & Valchev, T. 2001, A&A, 367, 884

Discussion

Ken Gayley: I presume that the material that's lost from the disk when it's being truncated is lost from the system; is that correct?

Atsuo Okazaki: The mass is stored in the Be disk.

Ken Gayley: Right, so the Be disk is decreting into the disk and then, when the companion comes around and causes a disruption, the material is lost from the system?

Atsuo Okazaki: Most of the mass is stored in the Be-star disk, in particular for low-to-moderate orbital eccentricities. But for high orbital eccentricity, a large fraction of the mass goes to the neutron star through the Roche lobe and most of the particles accrete onto the neutron star and do not escape from the system. Did I answer your question?

Ken Gayley: Well, yes, I think so but it wasn't what I was expecting. We learned a few days ago that it's hard to accrete matter onto a Be star. So what I was driving at is, if we turn the clock back a little bit to when the mass transfer that created the Be star occurred originally, presumably it made a disk for a while. During this process, would that have affected the mass transfer?

Atsuo Okazaki: But probably the disk mass will finally be lost by some violent mechanism which would produce type-II giant X-ray outbursts, I think.

Gloria Koenigsberger: You often see these X-ray outbursts interpreted in terms of a neutron star passing through the accretion disk. Is this still correct?

Atsuo Okazaki: Such a model *could* work only for a system of very high inclination ($i > 60^o$) or very high eccentricity ($e > 0.8$). In such extreme systems, such a mechanism *could* occur but for a very wide range of parameter space, it doesn't work. Resonant truncation always works, so the disk size is always smaller than the periastron distance.

Gloria Koenigsberger: So in the case of, e.g. 2S0114 that has these periodic X-ray outbursts every 2.8 hours, you are left with a problem that it is the neutron star that has to be producing these?

Atsuo Okazaki: Yes, that is a complicated point. But I imagine that in such a situation the disk should be deformed somehow and it will interact with the stellar wind. Negueruela's observations show that before the type-II giant outburst, the disk is warped. So the interaction with the stellar wind will become much stronger. Somehow, much of the disk mass goes to the neutron star and then causes the type II outburst. After a while, the disk is still disturbed significantly in a non-azimuthally symmetric way, so disk elongation will be seen and it will interact for a while with the neutron star at each periastron passage.